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SEISMIC PERFORMANCE ASSESSMENT OF A NOVEL SPRING BASED PISTON BRACING

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Abstract: Concentric Braced Frames (CBFs) are commonly used all over the world to resist seismic forces in buildings. Buckling, however, is a major concern for CBFs where they lose their strength and stiffness when subjected to load reversals during earthquakes. To tackle this problem, a novel easy-to-fabricate low-cost Spring Based Piston Bracing (SBPB) system is developed with single and double friction spring configurations. In this system, a brace member can carry a large magnitude of tension and compression forces where a special spring is employed in the piston cylinder. Stable and self-centering hysteresis behavior is achieved when the system is subjected to qualifying quasi-static loading. Strain rate effect is assessed, and comparable results are achieved without any performance degradation. Numerical simulation shows excellent matching with the test results. Two four-story braced steel buildings are designed: a) utilizing Buckling Restrained Braces (BRBs) and b) SBPB and their performances are compared in terms of interstory drift and residual drift. The proposed system experiences zero residual deformations but relatively larger drift values compared to BRBs.

1 INTRODUCTION

A recent study conducted by the Insurance Bureau of Canada estimated the overall loss after a 9.0-magnitude earthquake in British Columbia at almost $75 billion and a $61 billion loss after a 7.1-magnitude earthquake in the Quebec City-Montreal-Ottawa corridor (IBC, 2013), which clearly reflects the vulnerability of Canadian civil infrastructure. In order to avoid such scenarios, it is imperative to take immediate measures. One of the conventional techniques for resisting lateral forces is the Concentrically Braced Frames (CBFs), which are considered as one of the most widely used bracing systems (Roeder et al., 2012).

The resistance of braced steel frames to large earthquake ground motions relies on the performance of the bracing members under reverse cycles (tension and compression) of inelastic deformations. Many concentric bracing systems with different connection assemblies have been thoroughly studied by researchers in the past few decades, including but not limited to (Banihashemi et al. (2015); FitzGerald et al., 1989; Grande and Rasulo (2013); Gray et al. (2014); Lee & Bruneau, 2005; Maheri et al., 2003; McCormick et al., 2007; Palmer et al. (2012); Rai & Goel, 2003; Remennikov & Walpole, 1997; Roeder, 1989; Tremblay et al. (2003); Uriz and Mahin (2004); Yoo et al. (2008); Zamani et al. (2011)). The aforementioned bracings consist of braces, beams, columns, and their connections. The seismic performance of CBFs has inherent variability for several reasons, including the wide variation in the design procedures and therefore, fabrication for the brace, the gusset plate, the framing element, and their connections. One of the significant failure mechanisms in CBFs is buckling. Implementing a simple, yet efficient bracing system by absorbing compression force will avoid such phenomenon.

In order to resolve these issues, many bracing systems have been developed by researchers in the past few decades such as Buckling Restrained Bracings (BRBs) (Takeuchi et al., 2004a), CastConnex Scorpion Yielding Brace (Christopoulos et al., 2008), Memory Alloys for New Seismic Isolation Devices (MANSIDE) project braces (Dolce et al., 2000), Self Centering Energy Dissipation Device (SCED) (Robert Tremblay & Christopoulos, 2012) and Piston based Self-Centering (PBSC) bracing (Haque and Alam 2017) . BRB and Scorpion Yielding Brace resist seismic force by going into nonlinear range. They exhibit fat hysteresis loops, which contribute to the higher amount of damping, and thus, can reduce the velocity and acceleration of the system. Unfortunately, they do not have the self-centering property. Which means if there is a permanent deformation of the structure it is challenging to push the structure back to its original position.

The other two options SCED and MANSIDE braces offer re-centering capability but their construction is very complicated, and for this reason, they were not widely adopted by the construction industry. More studies have been conducted on the SCED system with enhanced working mechanisms. Xu et al. (2016) and Xu et al. (2017) carried out experimental and numerical studies on Pre-pressed Spring SCED (PS-SCED). This enhanced system combines the reliable energy dissipation of friction devices with a self-centering capacity provided by disc springs. However, construction complexity, as mentioned, and other issues related to minor residual deformation, sudden changes in stiffness, multiple design parameters and parameters dependency were the main drawbacks of these systems. Like the latter two options, several researchers recently conducted experimental as well as numerical studies testing and validating newly developed self-centering bracing systems including but not limited to (Gao et al., 2016; Qiu & Zhu, 2017; Speicher et al., 2017; Wu & Phillips, 2017). These include the use of SMA wires and rods, friction dampers, Fiber Reinforced Polymer (FRP) rods, and other techniques. All the adopted methods were targeting enhanced seismic performance of buildings in terms of maximizing energy dissipation and minimizing residual drifts. All the developed systems showed good aspects in terms of self-centering, efficient energy dissipation and flag shape hysteresis response. However, issues related to complexity and availability of some material are still the main drawbacks.

In this study, a novel Spring Based Piston Bracing (SBPB) system (Issa & Alam, 2018) is developed using a device commonly seen in mechanical systems, which is a cylinder-piston assembly. Using this assembly, a brace member can carry a large magnitude of tension and compression forces where a special spring is employed in the piston cylinder. Stable and self-centering hysteresis behavior is achieved when the system is subjected to qualifying quasi-static loading. The created coupled mechanism generated a hysteresis behavior which is favorable in lateral force resisting systems. The main objectives of the study are to determine the performance of the proposed bracing system under cyclic load. The bracing element is fabricated and then tested using the universal testing machine under quasi-static loading protocol. In this paper, the generated hysteresis curves for the new system are presented, and its performance is discussed. Finally, an assessment study was conducted to compare the seismic performance of two reference steel braced frame buildings equipped with SBPB and the BRBs.

2 DESCRIPTION AND DETAILS OF THE SYSTEM

The idea for the SBPB device can be summarized as follows. The system is anticipated to work mainly in a Chevron/V/X configuration bracing in buildings. This system can be employed for new and existing both steel and concrete structures. The proposed system is employed using a device commonly seen in mechanical systems, which is a cylinder-piston assembly. The tensile and compressive strength of a brace should be almost equal. For fabrication purposes, plan drawing, and sections are generated and shown in Figure 1. In this system (Figure 1), the configuration employs a double spring assembly where the piston head is located between them. In this configuration, the high strength steel rod is employed as the piston body. The piston rod is only used for compressing the springs in both directions. The two employed springs are the means for carrying the tensile/compressive force during loading cycles. The detailed system description which illustrates the working mechanism in this system can be found in Issa and Alam (2018). It is worth mentioning that the springs in this system only experience compression forces.

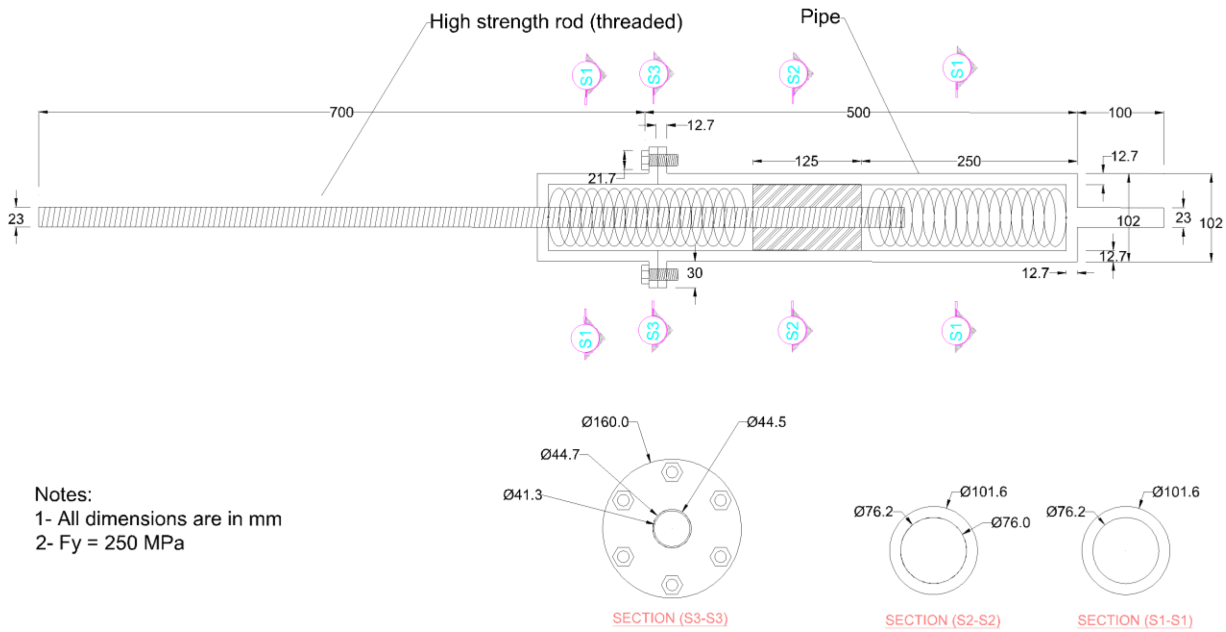

Figure 1: Basic Components of a Spring Based Piston Bracing

3 TESTING ARRANGEMENT

The objective of the experimental program is to investigate the cyclic behavior of bracing members in concentrically braced frames by means of cyclic axial tests. Quasi-static tests were carried out in the Applied Laboratory for Advanced Materials, and Structures (ALAMS) at the University of British Columbia (UBC)'s Okanagan campus. The specimen was tested using the MTS universal testing machine with a capacity of 500 kN. Considering the dimensional limit and characteristics of the machine and ease of specimen handling, the experimental set-up described in Figure 2 was adopted.

MTS control system and data acquisition system were both connected to the specimen to measure different test parameters. The MTS machine is equipped with a load cell to measure axial force, and vertical movement transducers to measure the movement of the MTS head. In addition to the latter transducer, an external LVDT was attached to the specimen to measure the exact vertical displacement of the piston. This could also measure any slippage that could occur in the MTS grip. Additionally, four strain gauges in total were attached to the piston tube and cylinder. For each component, one strain gauge was attached to each side, as shown in Figure 2.

The initial loading tests were run in displacement control in accordance with SAC Protocol load history (Venture, 1997). This load history is based on the interstorey drift angle which is the beam tip displacement divided by the story height in a frame structure equipped with the brace. Figure 2 shows the stepwise loading used in the test. The fixed displacements were applied to the grip of the brace specimen using the MTS hydraulic actuator at a rate of (25.4 mm/min.) as shown in Figure 2. The test specimen was subjected to symmetric reversed-cyclic loading to characterize its performance. Loading imposed by the MTS actuator was done at a sufficiently slow rate to prevent the development of any dynamic effects. Loading was applied continuously without intermittent stops in order to reduce any strain-rate effects. The effect of higher loading rates is also studied in detail and will be presented in the following sections.

The loading protocol was normalized to a maximum deformation of 40 mm. This is done because of the predefined travel stroke for the spring. Once the spring is fully compressed, it forms a solid stiff cylinder which can take substantial compressive force. In the trial with the original protocol where the maximum deformation amplitude was 75 mm, after exceeding the 40 mm threshold the specimen failed, and the test was stopped. Once the spring is entirely compressed, it cannot take any further deformation. Some other parts of the specimen had to take the deformation induced force. The grip next to the spring end failed where it penetrated the cylinder end plate. It is worth mentioning that as the spring can take such tremendous force when it gets fully compressed, such failures shall be expected either in the grips or buckling of the piston tube itself. Naturally, this can be controlled by increasing the number of rings in the spring, which will eventually increase the available travel stroke. It is worth mentioning that the current test specimens are proof-of-concept specimens used to verify the feasibility of the proposed system.

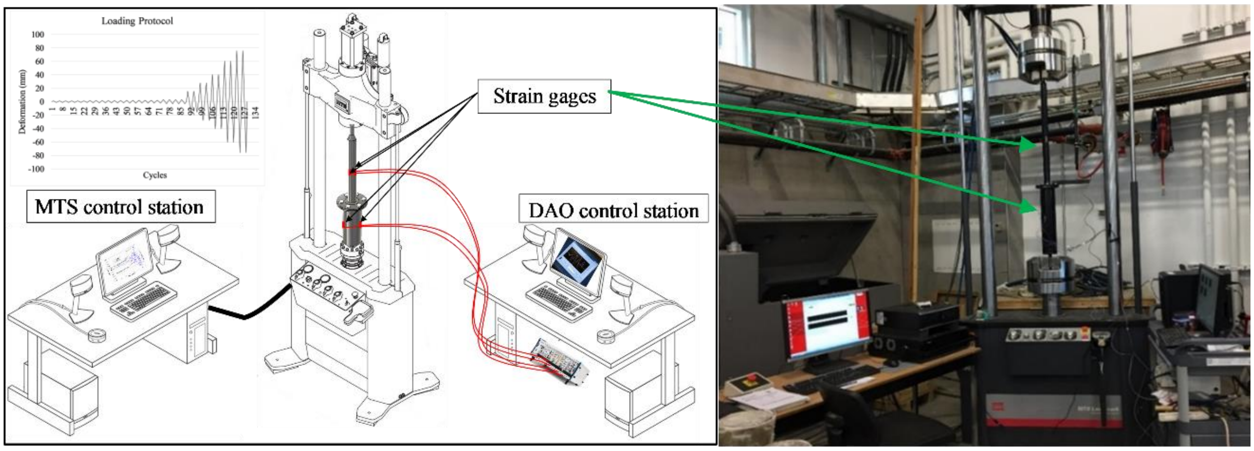

Figure 2: Test setup

4 RESULTS AND DISCUSSIONS

As mentioned in the previous sections, the double spring configuration employs two friction springs. The same loading protocol with the same loading rate was used to conduct the test. Strain gauges were only attached to the piston to ensure its fully elastic behavior throughout the test. Moreover, the proposed bracing system has been modeled in a structural analysis software SAP2000 (SAP, 2016). The loading protocol discussed in the previous section was implemented, and Fast Nonlinear Analysis (FNA) was conducted. To accurately simulate the hysteresis response of the spring, forces, stiffness, and displacements must be adequately defined. Figure 3 shows the different parameters used in the numerical simulation as per the values provided by the spring manufacturer. Figure 3 illustrates the obtained hysteresis response of the double spring assembly in SBPB. It is evident from the results that the system has stable, symmetric and repeatable force-deformation loops with no residual deformation.

Figure 3 shows excellent agreement between the experimental and numerical results. These results imply that the proposed system has the excellent self-centering ability and perfectly symmetric tension/compression load carrying capacities. The simple fabrication and simulation processes involved in developing this system highlights its feasibility and constructability. Although it may be noticed that the energy dissipation for the proposed system is not that significant, this issue can be easily overcome by employing more than one spring in different arrangements as will be discussed in the following sections. The test results validate the performance of the double spring configuration, which will be considered hereafter as the primary system in performing all other tests and simulations.

Parameter	Description	Value
Effective Stiffness	Input Spring Slope during the Loading Cycle (spring rate)	E=1.35kN/mm
Effective Damping	Input Damping = 66 for standard F-S1 grease	66
Initial (Non-slipping) Stiffness	Input Spring Slope during the Loading Cycle (spring rate)	E=1.35kN/mm
Slipping Stiffness (Loading)	Input Spring Slope During the Unloading Cycle	F=0.46kN/mm
Slipping Stiffness (Unloading)	Input Spring Slope During the Unloading Cycle	F=0.46kN/mm
Pre-compression Displacement	Input Preload Travel	0
Stop Displacement	Input Total Spring Travel minus Preload Travel	253.2mm

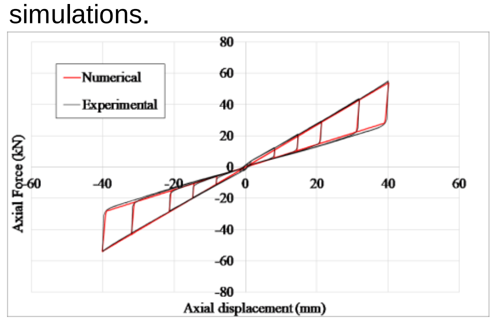

Figure 3: Parameters and their values in friction spring along with results

5 SEISMIC PERFORMANCE ASSESSMENT

An assessment study was performed to compare the seismic performance of the SBPB with a relatively newly developed and fast emerging bracing system, which is the BRB. A reference building of 4 stories located in Vancouver, BC was considered for the purpose of this specific task. Using the Natural Resources Canada website (NRC, 2017), the seismic hazard of Vancouver city for 2% in 50 years was calculated.

5.1 Reference Building

Three-dimensional finite element models were developed for the building investigated in the present study using the structural analysis and design program ETABS (ETABS, 2016). Figure 4 depicts the layouts and 3D models of the reference 4-story building. The building considered in this study comprises a hypothetical 4 story office building with a 225 sq. m area located in Vancouver, BC. The building has a typical story height of 3.8 m. The building was designed in the current study according to modern building codes (CSA, 2014; NBCC, 2015). Wind loads are estimated using (NBCC, 2015) based on an exposure category "C" and basic wind speed of 135 mph. The seismic loads were also estimated using (NBCC, 2015) with a soil class "C". The 0.2 sec spectral acceleration, the 1.0 sec spectral acceleration and the Long-period transition period are 0.839g, 0.421g, and 8s, respectively. The response modification factor (R) and the importance factor (I) were selected as per the structural system and risk category which considered herein as an office building. The live and dead loads for roof and floors considered in the design are shown in Figure 4. An iterative design process was carried out using ETABS (ETABS, 2016) under all load combinations recommended by CSA (2014). This was undertaken by targeting a Demand over Capacity (D/C) ratio as close as 1.0 to guarantee both safety and cost-effective design. It is important to note that the design procedure of this study may not be the typical design practice in everyday applications. In many cases, the over-strength values may be very high, and the demand/capacity ratios may be considerably lower than the unity. Such practices will not satisfy the optimum design concept where both satisfactory performance and cost-effective design is achieved.

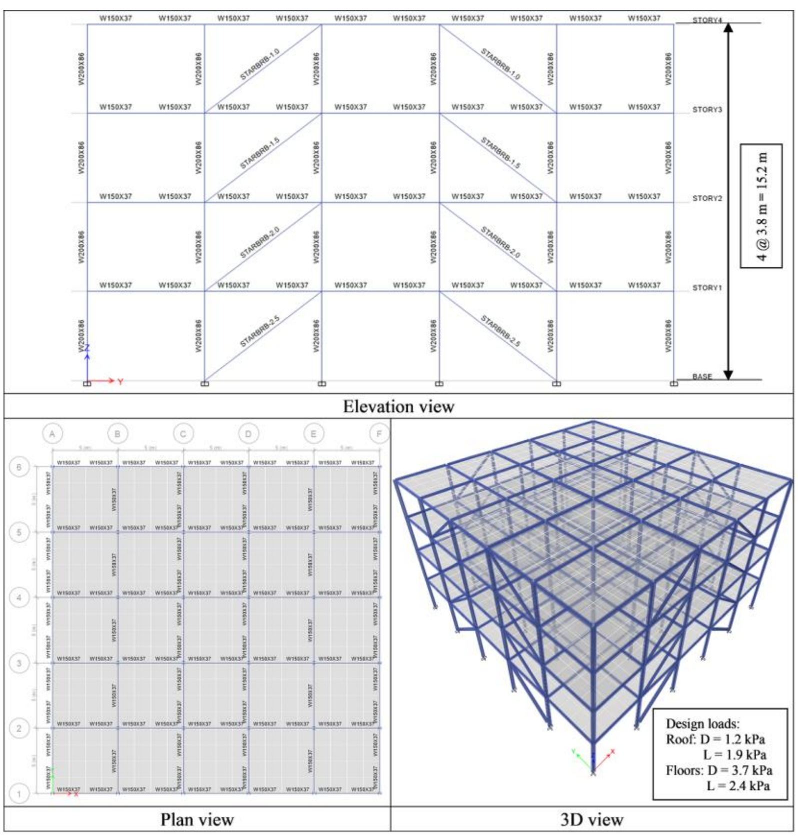

Figure 4: 4-story reference building views

5.2 Earthquake Records

In this study, twenty far-field earthquake records are used for seismic assessment of the reference building. This is done for practical reasons since there are many issues in the characterization of near-field hazards as well as ground motion effects. On the other hand, for this analysis, only two horizontal orthogonally separated records are used from each of the 20 selected events. The vertical component of the excitation is ignored as this direction is not considered of key importance for collapse assessment. Table 1 depicts the selected earthquake records with their properties and the number and size of steps used in each record. As per FEMAP695 (2009) guideline, the ground motion records are supposed to be collectively scaled (anchored) to a specific ground motion (response spectra of the seismic zone under consideration) intensity so that the median spectral acceleration of the set matches the MCE spectral acceleration at the fundamental period of the index archetype. A computer program for signal processing of strong-motion data, (Antoniou & Pinho, 2012), was used to match the considered ground motions. Figure 5 shows the mean spectra of the scaled 20 far-field ground motion record set compared to the Vancouver 2% in 50-year soil class "C" response spectra.

Table 1: Summary of earthquake records

EQ		Earthquake		Recording Station	Epic entra l	PGA_{max}	PGV_{max}	PGV/PGA	Power	Period	Total	time
No	M	Year	Name	Name		(g)	(cm/s.)	(sec)	Spectrum		steps	step
1	7.4	1978	Tabas		1.2	0.90	108	0.124	0.188	0.759	2498	0.02
2	7.4	1978	Tabas		1.2	0.96	103.8	0.11	0.135	4.551	2498	0.02
3	7	1989	Loma Prieta	Los Gatos	3.5	0.70	170	0.246	0.226	0.63	2498	0.01
4	7	1989	Loma Prieta	Los Gatos	3.5	0.46	89.33	0.203	0.284	0.64	2498	0.01
5	7	1989	Loma Prieta	Lex. Dam	6.3	0.67	175	0.266	0.377	1.078	3997	0.01
6	7	1989	Loma Prieta	Lex. Dam	6.3	0.37	67.34	0.189	0.179	0.683	3997	0.01
7	7.1	1992	C. Mendocino	Petrolia	8.5	0.63	123.4	0.201	0.188	0.635	2998	0.02
8	7.1	1992	C. Mendocino	Petrolia	8.5	0.65	91	0.145	0.356	0.745	2998	0.02
9	6.7	1992	Erzincan	Erzincan	2	0.42	117	0.281	0.256	2.276	4154	0.005
10	6.7	1992	Erzincan	Erzincan	2	0.45	57	0.13	0.224	1.781	4154	0.005
11	7.3	1992	Landers	Lucrene V. Stn.	1.1	0.69	133.4	0.194	0.064	4.096	12319	0.004
12	7.3	1992	Landers	Lucrene V. Stn.	1.1	0.79	69	0.09	0.149	0.09	12319	0.004
13	6.7	1994	Nothridge	Rinaldi	7.5	0.87	171	0.2	0.173	1.28	2988	0.005
14	6.7	1994	Nothridge	Rinaldi	7.5	0.38	59.7	0.16	0.14	0.301	2988	0.005
15	6.7	1994	Nothridge	Olive View	6.4	0.72	120	0.17	0.217	2.341	2998	0.02
16	6.7	1994	Nothridge	Olive View	6.4	0.58	52.9	0.092	0.197	0.509	2998	0.02
17	6.9	1995	Kobe	JMA	3.4	1.07	157	0.15	0.273	0.836	2998	0.02
18	6.9	1995	Kobe	JMA	3.4	0.56	71	0.128	0.201	1.28	2998	0.02
19	6.9	1995	Kobe	Takatori	4.3	0.77	170.5	0.225	0.721	1.205	4008	0.01
20	6.9	1995	Kobe	Takatori	4.3	0.42	62.5	0.153	0.346	1.205	4008	0.01

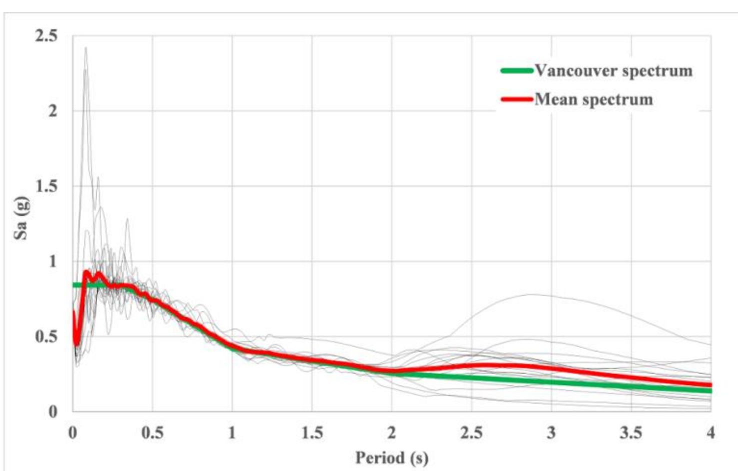

Figure 5: Response spectra of earthquake records matched to Vancouver response spectrum

5.3 Time History Analysis

Time history analysis (THA) is a step-by-step analysis of the dynamic response of a structure to a specified loading that may vary with time. THA is used to determine the seismic response of a structure under dynamic loading of the representative earthquakes. In the current study, 20 far-field records were used, as mentioned previously, to conduct the THA. Scaled to the design value of the study area, i.e. Vancouver, the two references models were analyzed and the interstory drift ratios were obtained and plotted against the building floors, as shown in Figure 6. The maximum interstory drift ratio for the BRB frame building was around 1.45%, while for the SBPB was around 1.8%. The average interstory drift ratios were 0.9% and 1.2% for the BRB and the SBPB buildings, respectively.

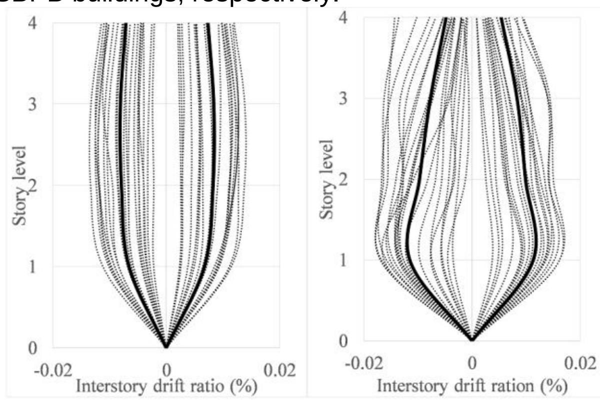

Figure 6: Maximum interstory drift ratios under the 20 earthquake records (a) BRB, and (b) SBPB

5.4 Braces Hysteresis

One of the key results obtained from the THA was the hysteresis responses of different brace elements in the two reference buildings. A bracing element which can provide stable and repeated hysteresis force-deformation loops is highly desirable. BRBs provide symmetric, stable and repeated loops; however, the brace core will experience residual deformation, which is the undesired outcome. On the other hand, nevertheless, the SBPB provides as stable, repeated, and symmetric loops as the BRB but it experiences almost zero residual deformation after the earthquake event. This phenomenon is pronounced in the four brace elements along the building floor as shown in Figure 7. Alternatively, because of the lower single brace element stiffness in SBPB compared to the BRB, higher deformation is observed for all the elements, but this value is still in the safe range of braced frames as shown in Figure 6.

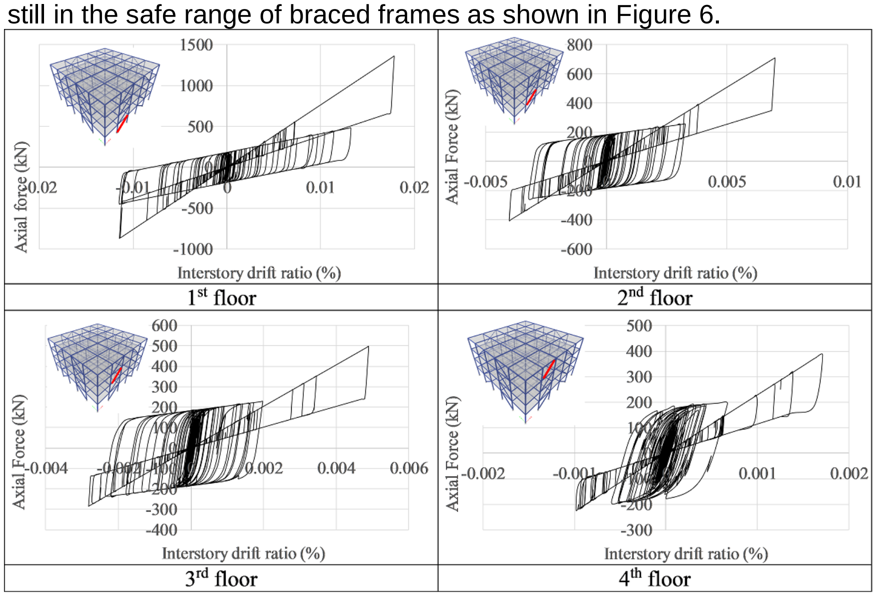

Figure 7: Hysteresis behavior comparison for NF1

5.5 Residual Interstory Drift Ratios

Residual drifts are the permanent deformations of a structure that remain at the end of a seismic excitation, and they are caused by the nonlinear behavior of the yielding components in the system. Several studies have revealed that residual drifts after earthquakes that are greater than 0.5% in buildings may represent a complete loss of the structure from an economic viewpoint (Erochko et al., 2010; Fahnestock et al., 2007).

The residual drifts values were obtained for the two reference buildings and plotted against the story level as shown in Figure 8. Although the maximum interstory drift ratios experienced by the SBPB building were slightly larger than those in the BRB building, the residual drifts were considerably smaller. In the SBPB building, most of the records (except three) generated a residual drift less than 0.0005%. On the other hand, BRB frame building experienced larger residual drifts where values exceeded 0.01% in many cases as shown in the figure. The residual deformations observed in the BRB frame building was observed in one direction as is justified by the presence of the steel core in the BRB which yields and experiences permanent deformation; hence, could not self-center with the accumulation of permanent strains, unlike the SBPB system.

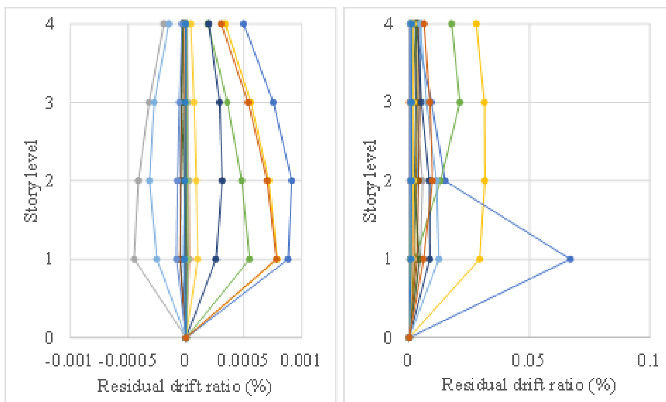

Figure 8: Residual Interstory drift ratios for (a) SBPB, and (b) BRB

5.6 Story Acceleration Responses

Although the deformation demand is the primary concern in this analysis, peak floor acceleration is also examined, as shown in Figure 9. It is seen that the distribution of peak floor accelerations is uniform over the building height for both systems. However, SBPB showed more uniform behavior compared to the BRB. Also, for SBPB, the mean value for the peak acceleration was marginally less than the value observed in the BRB. This can be attributed to the fact that the overall stiffness of the BRB building is higher than the SBPB building. This stiffer response for the BRB can be observed from the marginally lower interstory drift ratio as Figure 6 shows, which yielded a slightly higher acceleration response.

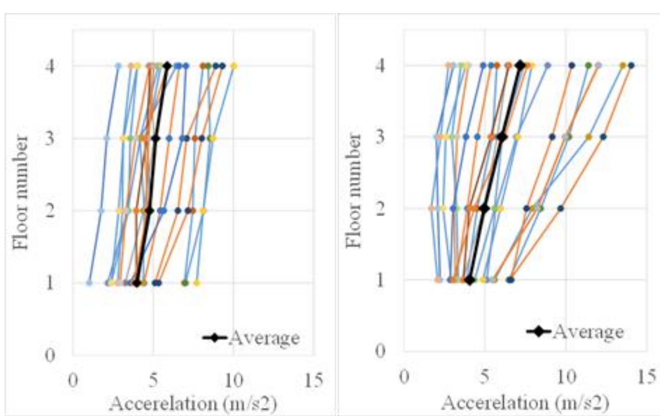

Figure 9: Peak floor accelerations over the building height: (a) SBPB, and (b) BRB

6 Conclusions

This paper described the development and seismic performance assessment of a novel Spring Based Piston Bracing for the civil engineering structures. Design drawings were generated, and a test specimen was fabricated and tested several times under quasi-static loading protocol where stable and self-centering hysteresis behavior was achieved. The generated hysteresis curves for the new system were presented, and its performance was discussed. An assessment study was conducted to compare the seismic performance of two reference steel braced frame buildings equipped with SBPB and the BRBs. The major findings of the study are highlighted as follows:

- The double spring configuration showed perfect self-centering ability with good energy dissipation. Finite element models were generated, and fast nonlinear analysis was conducted using the same loading protocol. Excellent agreement in the cyclic response of the proposed system for the experimental and numerical results was achieved.
- A 4-story building was designed using BRB and SBPB systems, and their seismic performance was compared. The SBPB experienced relatively higher drifts compared to BRB, but it remained in the safe margin limits. SBPB overcomes the BRB in terms of minimal residual deformation and self-centering ability.
- The proposed system overcomes the other available self-centering systems in its simplicity and constructability. The used friction-spring dissipate energy efficiently even with high loading amplitudes and can sustain large deformations by means of increasing the number of rings. Such bracing will not only be a cost-effective and efficient technique for new buildings but also for retrofitting older deficient structures.

7 Acknowledgements

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